

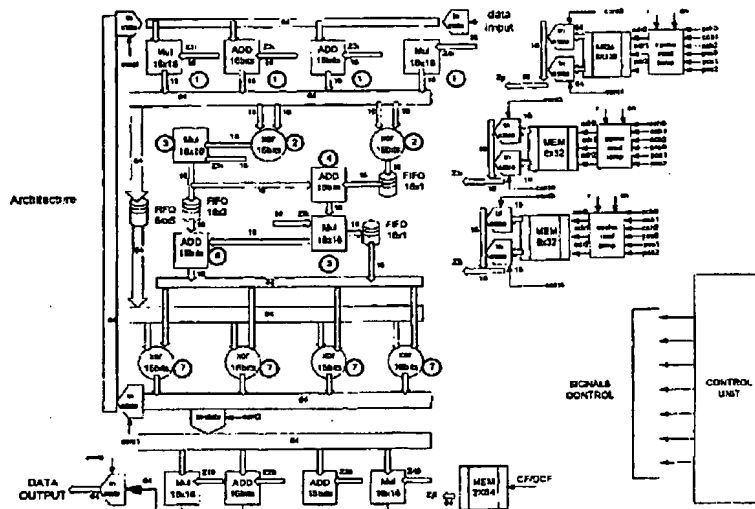
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(54) Title: **A METHOD FOR THE HARDWARE IMPLEMENTATION OF THE IDEA CRYPTOGRAPHIC ALGORITHM - HiPCRYPTO**

(57) Abstract: HiPCrypto is the hardware implementation of the most secure private key cryptographic algorithm: IDEA (International Data Encryption Algorithm), through the exploitation of spatial and temporal parallelism techniques in order to achieve the processing speed required by ATM and Gigabit networks.

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Description of the Invention "A METHOD FOR
THE HARDWARE IMPLEMENTATION OF THE IDEA CRYPTOGRAPHIC
ALGORITHM - HiPCrypto"

TECHNICAL FIELD

5 HiPCrypto is a hardware architecture proposal
for the IDEA cryptographic algorithm, in which were used
techniques for the exploitation of spatial and temporal
parallelism, in order to reach the processing speeds
required by real time applications and high speed data
10 communication networks such as ATM.

Nowadays, a world tendency exists for the use
of networks that provide different types of
Telecommunication services such as the Integrated Service
Data Network (ISDN). These types of networks should provide
15 a wide range of services from telephone and cable TV to
video conference.

The technological progress of transmission
data networks pushed the development of cryptographic
algorithm that became progressively more complex and
20 robust. They are widely used by private and governmental
organizations as well as individuals that need to ensure
secrecy in data communication.

The increasing complexity of recent
cryptographic algorithms require high processing
25 capabilities due to the large number of arithmetic and
logic operations that have to be executed, in some cases
for real time applications like in video confereces.

PREVIOUS TECHNIQUES

Direct hardware implementation of
30 cryptographic algorithms can ensure high processing speeds
required by current and future applications in data

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transmission and eliminate a potential bottleneck in data communication networks that require high security levels.

Consequently, several cryptographic algorithms were totally or partially implemented as
5 Application Specific Integrated Circuits.

Several hardware and software implementations have been developed in the past decade for the Data Encryption Standard (DES), the most popular private key cryptographic algorithm. Table 1 shows the performance
10 obtained for some software implementations in different platforms. Table 2 shows the performance obtained for some dedicated hardware implementations. From table 2 one can see that the 6868 integrated circuit from VLSI Technology reaches up to 512Mbit/s, which is not sufficient to support
15 some high end ATM applications. Furthermore, it cryptanalysis on DES proved that it is weaker than some recent private key cryptographic algorithms like IDEA. Few hardware implementations of IDEA or its predecessors were reported in the literature. For example, an ASIC that
20 implements the PES algorithm, which originated IDEA, has reached up to 55 Mbits/s at 25 MHz.

DETAILED DESCRIPTION

IDEA cryptographic algorithm

The first form of the IDEA algorithm, was
25 created by " Xuejia Lai and James Massey " in 1990 (US05214703 patent) and was called PES (Proposed Encryption Standard). In 1991, the algorithm was strengthened and was called IPES (Improved Proposed Standard Encryption). In 1992 IPES was called IDEA (International Data Encryption
30 Algorithm), and is actually considered by many specialists

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in the field of cryptography as the strongest existing symmetrical algorithm.

IDEA is a symmetric, block-oriented cryptographic algorithm, which uses 128-bit keys (thus making it practically immune to brute-force attacks) and 64-bit plaintext blocks. IDEA is build upon a basic function, which is iterated multiple times. As shown in Figure 1 the basic function is iterated eight times. The first iteration operates on the input 64-bit plaintext block and the successive iterations operate on the 64-bit block obtained from the previous iteration. After the last iteration, a final transformation step produces the 64-bit ciphertext block.

Figure 1 shows the structure of the basic function. It involves three simple operations: bitwise exclusive-or, addition modulo 2^{16} (addition, ignoring the "overflow") and multiplication modulo $2^{16} + 1$ (multiplication, ignoring the "overflow"). For each iteration, the 64-bit input block is divided into four 16-bit sub-blocks. In Figure 1, X1, X2, X3 and X4 denote the four 16-bit input sub-blocks used by the each iteration. The 64-bit block produced by each iteration is also constituted by four 16-bit sub-blocks. In Figure 1, Y1(i), Y2(i), Y3(i) and Y4(i) denote the four sub-blocks resulting from the each iteration. The 128-bit key is divided into 52 16-bit sub-keys (sub-key generation is discussed ahead). Six sub-keys are used in each iteration and four sub-keys are used in the final transformation. In Figure 1, Z1(i), Z2(i), Z3(i), Z4(i), Z5(i) and Z6(i) denote the six sub-keys used in each iteration. The operations performed in the each iteration are:

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1. Multiply sub-block $X1(i)$ by sub-key $Z1(i)$
2. Add sub-block $X2(i)$ and sub-key $Z2(i)$
3. Add sub-block $X3(i)$ and sub-key $Z3(i)$
- 5 4. Multiply sub-block $X4(i)$ by sub-key $Z4(i)$
5. XOR the results of (1) and (3)
6. XOR the results of (2) and (4)
7. Multiply the result of (5) by sub-key $Z5(i)$
8. Add the results of (6) and (7)
- 10 9. Multiply the result of (8) by sub-key $Z6(i)$
10. Add the results of (7) and (9)
11. XOR the results of (1) and (9)
12. XOR the results of (3) and (9)
13. XOR the results of (2) and (10)
- 15 14. XOR the results of (4) and (10)

The outputs of the iteration are the four sub-blocks produced by steps (11) to (14). The two inner sub-blocks from steps (12) and (13), $Y2(i)$ to $Y3(i)$, are swapped, except for the last iteration.

- 20 Figure 1 shows the structure of the final transformation. In this figure, $Z1(9)$ to $Z4(9)$ denote the four 16-bit sub-keys and $Y1$ to $Y4$ denote the four 16-bit sub-blocks of the 64-bit ciphertext block. The operations performed in the final transformation are:

- 25 15. Multiply sub-block $X1$ by sub-key $Z1(9)$ to obtain $Y1$
16. Add sub-block $X2$ and sub-key $Z2(9)$ to obtain $Y2$
17. Add sub-block $X3$ and sub-key $Z3(9)$ to obtain $Y3$
18. Multiply sub-block $X4$ by sub-key $Z4(9)$ to obtain $Y4$

- 30 The encryption and decryption sub-keys are generated from the single 128-bit key. Encryption sub-keys are generated as follows. Initially, the 128-bit key is

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divided into eight 16-bit sub-keys. Six of these sub-keys, Z1(1) to Z6(1), are used in the first iteration. The two remaining sub-keys, Z1(2) and Z2(2), are for the second iteration. The original 128-bit key is then rotated left by 25 bits and the resulting key is again divided into eight 16-bit sub-keys. Four sub-keys, Z3(2) to Z6(2), are grouped with Z1(2) and Z2(2) and destined to the second iteration. The other four sub-keys, Z1(3) to Z4(3), are to be used in the third iteration. Next, the key is again rotated left by 25 bits, divided into eight 16-bit sub-keys and these sub-keys are grouped properly. This process is repeated each of the sub-keys for the eight iterations and for the final transformation have been generated. Decryption sub-keys are calculated as either the additive or the multiplicative inverses of the encryption keys.

As stated, the main goal in designing HiPCrypto is to obtain a device which would meet the performance requirements of applications in current and future high-speed data networks. This was achieved by including parallel execution techniques into the design of HiPCrypto's architecture. There are two opportunities for exploiting parallelism in the IDEA algorithm: in the execution of its basic function and in the iterations of this function.

Examining the data flow shown in Figure 1, one can identify groups of operations that are data independent. In each group, one operation does not use the results produced by other operations in the group. The sets of independent operations are: the multiply and add operations in steps (1) to (4); the exclusive-or operations in steps (5) and (6); and the exclusive-or operations in

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steps (11) to (14). These independent operations can be performed simultaneously, provided the architecture incorporates multiple functional units dedicated to the execution of each of them.

5 By including multiple functional units in the architecture, we are making use of spatial parallelism. Temporal parallelism can also be employed in the execution of the basic function, by overlapping in time the operations upon distinct plaintext blocks. In this way,
10 multiple blocks can be encrypted (or decrypted) simultaneously, instead of sequentially. This temporal parallelism was implemented with the pipeline shown in Figure 2.

Stage 1 contains two add and two multiply
15 units that perform in parallel the independent operations in steps (1) to (4) of the algorithm.

Stage 2 contains two exclusive-or units to execute the operations in steps (5) and (6) in parallel.

Stages 3, 4, 5 and 6 contain a single add or
20 multiply unit and they execute, respectively, the operations in steps (7), (8), (9) and (10) of the algorithm.

Stage 7 has four exclusive-or units to execute steps (11) to (14) in parallel.

25 The last stage has two add units and two multiply units and performs the algorithm's final transformation (see Figure 2). This stage will be referred to as the output stage.

In Figure 2, one can notice the inclusion of
30 between stages of the pipeline. These queues temporarily hold data forwarded between non-adjacent stages. For

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instance, stage 7 operates on sub-blocks from stages 1 and 5 (see Figure 1).

A sub-block from stage 1 arrives five cycles before the corresponding sub-block from stage 5, and during this time interval it remains in one of the queues connecting stages 1 and 7. When the sub-block from stage 5 is available, the sub-block in the front of the queue is dequeued and paired with the sub-block from stage 5. A queue is needed along the shortest path (in number of stages) between two non-neighbor stages. The size of each queue is indicated in figure 2.

The final aspect in HiPCrypto's architecture concerns the generation and storage of the sub-keys. To generate the encryption sub-keys, it would be necessary a circuitry for the rotation and sub-division of the 128-key. Moreover, the generation of the decryption sub-keys would require an arithmetic unit for the calculation of additive and multiplicative inverses. The inclusion of this additional hardware would only be reasonable if the key changes very frequently, say, every few blocks. But that is not the common case in a private-key cryptosystem: typically, the key shared by a group of partners is changed in a long term basis (days or weeks, for example). For this reason, only sub-key storage is provided. Sub-keys are generated externally by the host system, and then downloaded into the chip.

Architecture of HiPCrypto

The HiPCrypto architecture, Figure 3, executes a complete iteration of the algorithm. This architecture is composed of six 16-bit multipliers, six

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16-bit adders and six 16-bit exclusive-or, memories for sub-key storage, buffers, tri-states and a control unit.

The operations contained in each stage of the pipeline, will be executed in an only machine cycle and
5 since there are 7 pipeline stages, it will cipher (resp. decipher) 7 64 bits blocks for each execution of the algorithm.

The HIPCrypto was designed to offer four kinds of configurations, ie, 1, 2, 4 or 8 integrates in
10 series (table 3).

Each pipeline segment is executed in one clock cycle. For one chip configuration, seven 64 bits blocks are processed each 56 (7 x 8) machine cycles. For 2 chips seven 64 bits blocks are processed each 28 (7 x 4)
15 machine. For 4 chips configuration seven 64 bits blocks are processed each 14 (7 x 2) machine cycles. For 8 chips configuration seven 64 bits blocks are processed each 7 (7 x 1) machine cycles, that is to say, one 64 bits block for each machine cycle.

20 The proposed HIPCrypto's structure can be adapted to different uses. The adequate compromise between throughput and cost can be obtained by selecting the number of chips operating in series.

The signals used for selecting the chip
25 configurations were divided in two groups: three signals that will define the configuration cch <2:0> and three signals that will define the position of the chip into the chain pos <2:0>. Tables 4 and 5 show respectively the configurations and the possible positions.

30 The sub-keys are stored in 4 RAMs according to Figures 3 and 4.

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For sub-keys $Z1(i)$, $Z2(i)$, $Z3(i)$ and $Z4(i)$, a 128 bits x 8 memory is used. The first 64 bits of each memory position, least significant bits, store the cipher sub-keys (positions 0 to 63) and the last 64 bits, most
5 significant bits (positions 64 to 127), store the decipher sub-keys. The selection to execute the algorithm in cipher or decipher mode is made through the bus selection (see Figures 3 and 4).

For sub-keys $Z5(i)$ and $Z6(i)$, two 32 bits x 8
10 RAMs are used, where the 16 least significant bits (0 to 15), store the cipher sub-keys $Z5(i)$ and $Z6(i)$, and the 16 bits most significant store the decipher sub-keys.

For the sub-keys $Z1(9)$, $Z2(9)$, $Z3(9)$ and $Z4(9)$, a 64 bits x 2 memory is used.

15 Control Unit

The control unit (see Figure 3) is the operational block that controls the operation of the architecture. This unit together with some extra circuits is responsible for the generation of the control signals.
20 The main functions of this unit are described in the following.

The control unit selects ciphering and deciphering modes, i.e. selecting the cipher and decipher sub-keys respectively in each embedded memory.

25 The control unit also allows the correct initialization, feeding and synchronization of the pipeline stages by generating all enables and reset signals for each internal block.

The output stage will only be used by the
30 last chip in each configuration. This selection is also

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performed by the control unit through the selected configuration for each chip.

HIPCrypto performance

Table 7 shows some examples of the
5 performance of HIPCrypto implemented in a two metal layer
0,7 micron CMOS technology.

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CLAIMS

1. A METHOD FOR THE HARDWARE IMPLEMENTATION OF THE IDEA CRYPTOGRAPHIC ALGORITHM - HIPCrypto, patented in the USA under the no. US05214703, that makes use of a
5 seven stages pipeline to be implemented as a synchronous circuit, that will be referred as micro-pipeline, coupled to an output stage as described in figure 2; so that each stage of the pipeline supplies partial results for the following stage and receives partial results from the
10 previous stage at each clock pulse of the synchronous circuit; so that there exists a feedback from stage number 7 to stage number 1, controlled by the digital control unit so that, for each of 16 rounds for ciphering a 64 bits block, the first stage of the pipeline is fed with partial
15 results from the output of the seventh pipeline stage and that the pipeline is fed with a new block when the ciphering process is completed; and the sub-keys used in the data ciphering and deciphering processes, in agreement with the definition of IDEA the algorithm, is stored in
20 four dedicated memory units.

2. A METHOD FOR THE HARDWARE IMPLEMENTATION OF THE IDEA CRYPTOGRAPHIC ALGORITHM - HIPCrypto, in agreement with claim 1 in which the operations 1, 2, 3 and 4 of the description of the IDEA cryptographic algorithm is
25 executed by two 16 bits multiplier units and two 16 bits adder units; and these units compose pipeline stage number as described in figure 2; so that this stage receives, either a new 64 bits block from data input or a partial result from the seventh stage and the ciphering or
30 deciphering sub-keys corresponding to this stage as described in the figures 2 and 3; so that the inputs and

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outputs of this stage are connected to input and output registers respectively.

3. A METHOD FOR THE HARDWARE IMPLEMENTATION
5 OF THE IDEA CRYPTOGRAPHIC ALGORITHM - HIPCrypto, in
agreement with claim 1 in which the operations 5 and 6 of
the description of the IDEA cryptographic algorithm are
executed by two 16 bits exclusive-or units; and these units
compose stage number two of the pipeline as described in
10 the figure 2; so that this stage receives partial results
from the first stage as described in the figures 2 and 3;
so that the inputs and outputs of this stage are connected
to input and output registers respectively.

4. A METHOD FOR THE HARDWARE IMPLEMENTATION
15 OF THE IDEA CRYPTOGRAPHIC ALGORITHM - HIPCrypto, in
agreement with claim1 in which the operation 7 of the
description of the IDEA cryptographic algorithm is executed
by a 16 bits multiplier unit; and this unit composes stage
number three of the pipeline as described in the figure 2;
20 so that this stage receives partial results from the
previous stage and ciphering and deciphering sub-keys
corresponding to this stage as described in figures 2 and
3; and that the inputs and outputs of this stage are
connected to input and output registers respectively.

25 5. A METHOD FOR THE HARDWARE IMPLEMENTATION
OF THE IDEA CRYPTOGRAPHIC ALGORITHM - HIPCrypto, in
agreement with claim1 in which the operation 8 of the
description of the IDEA cryptographic algorithm is executed
by a 16 bits adder unit; and this unit composes stage
30 number four of the pipeline as described in the figure 2;
so that this stage receives partial results of the stages 2

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and 3 as described in the figure 2; and that the inputs and outputs of this stage are connected to input and output registers respectively.

5 6. A METHOD FOR THE HARDWARE IMPLEMENTATION
OF THE IDEA CRYPTOGRAPHIC ALGORITHM - HIPCrypto, in
agreement with claim1 in which the operation 9 of the
description of the IDEA cryptographic algorithm is executed
by a 16 bits multiplier unit; and this unit composes stage
number five of the pipeline as described in figure 2; so
10 that this stage receives partial results from the previous
stage and ciphering and deciphering sub-keys corresponding
to this stage as described in the figures 2 and 3; and that
the inputs and outputs of this stage are connected to input
and output registers respectively.

15 7. A METHOD FOR THE HARDWARE IMPLEMENTATION
OF THE IDEA CRYPTOGRAPHIC ALGORITHM - HIPCrypto, in
agreement with claim1 in which the operation 10 of the
description of the IDEA cryptographic algorithm is executed
by a 16 bits adder unit; and this unit composes stage
20 number six of the pipeline as described in the figure 2; so
that this stage receives partial results of stages 3 and 5
as described in figure 2; and that the inputs and outputs
of this stage are connected to input and output registers
respectively.

25 8. A METHOD FOR THE HARDWARE IMPLEMENTATION
OF THE IDEA CRYPTOGRAPHIC ALGORITHM - HIPCrypto, in
agreement with claim1 in which the operations 11, 12, 13
and 14 of the description of the IDEA cryptographic
algorithm are executed by four 16 bits exclusive-or units;
30 and these units compose stage number seven of the pipeline
as described in figure 2; so that this stage receives

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partial results from stages 1, 5 and 6 as described in the figure 2; and that the inputs and outputs of this stage are connected to input and output registers respectively.

9. A METHOD FOR THE HARDWARE IMPLEMENTATION OF THE IDEA CRYPTOGRAPHIC ALGORITHM - HIPCrypto, in agreement with claim1 in which the operations 15, 16, 17 and 18 of the description of the IDEA cryptographic algorithm are executed by two 16 bits multiplier units and for two 16 bits adder units; and these units compose the output stage of the pipeline as described in figure 2; so that this stage receives partial results from stage 7 of the pipeline and ciphering and deciphering sub-keys corresponding to the output stage as described in figures 2 and 3; and that the inputs and outputs of this stage are connected to input and output registers respectively.

10. A METHOD FOR THE HARDWARE IMPLEMENTATION OF THE IDEA CRYPTOGRAPHIC ALGORITHM - HIPCrypto, in agreement with claim1, in which the sub-keys used in ciphering and deciphering process are stored in four dedicated memories according to figure 4 as follows: ciphering sub-keys $Z1(i)$, $Z2(i)$, $Z3(i)$ and $Z4(i)$ (i from 1 to 8) and deciphering sub-keys $Z1(i)$, $Z2(i)$, $Z3(i)$ and $Z4(i)$ (i from 1 to 8) stored in a 128 bits x 8 memory; ciphering sub-keys $Z5(i)$ (i from 1 to 8) and deciphering sub-keys $Z5(i)$ (i from 1 to 8) stored in the first 32 bits x 8 memory; ciphering sub-keys $Z6(i)$ (i from 1 to 8) and deciphering sub-keys $Z6(i)$ (i from 1 to 8) stored in the second 32 bits x 8 memory; ciphering sub-keys $Z1(9)$, $Z2(9)$, $Z3(9)$ and $Z4(9)$ and deciphering sub-keys $Z1(9)$, $Z2(9)$, $Z3(9)$ and $Z4(9)$ stored in the 64 bits x 2 memory.

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11. A METHOD FOR THE HARDWARE IMPLEMENTATION
OF THE IDEA CRYPTOGRAPHIC ALGORITHM - HIPCrypto, in
agreement with claims 1 and 2, in which a second pipeline
level, denominated macro-pipeline, allows the concatenation
5 of 2, 4 or 8 circuits operating with a micro-pipeline of
seven stages as indicated in the table 3.

12. A METHOD FOR THE HARDWARE IMPLEMENTATION
OF THE IDEA CRYPTOGRAPHIC ALGORITHM - HIPCrypto, in
agreement with claims 1 and 2, in which " first-in first-
10 out "(FIFO) memories are used in order to synchronize the
data provenient from non adjacent stages in the following
way: a 64 bits x 5 positions FIFO connecting stages 1 and
7, a 16 bits x 2 positions FIFO connecting stages 3 and 6,
a 16 bits x 1 position FIFO connecting stages 2 and 4, a 16
15 bits x 1 position FIFO connecting stages 5 and 7, as
described in the figure 3.

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DRAWINGS

Table 1

PAGE 41/41 * RCVD AT 4/11/2007 10:33:52 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-5/15 * DNIS:2738300 * CSID:(661) 460-1986 * DURATION (mm-ss):21-40